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Greenhouse gas emissions from global agriculture are increasing at around 1% per annum, yet substantial cuts in emissions are needed across all sectors[1]. The challenge of reducing agricultural emissions is particularly acute, because the reductions achievable by changing farming practices are limited[2,3] and are hampered by rapidly rising food demand[4,5]. Here we assess the technical mitigation potential offered by land sparing - increasing agricultural yields, reducing farmland area and actively restoring natural habitats on the land spared[6]. Restored habitats can sequester carbon and can offset emissions from agriculture. Using the United Kingdom as an example, we estimate net emissions in 2050 under a range of future agricultural scenarios. We find that a land-sparing strategy has the technical potential to achieve significant reductions in net emissions from agriculture and land-use change. Coupling land sparing with demand-side strategies to reduce meat consumption and food waste can further increase the technical mitigation potential, however economic and implementation considerations might limit the degree to which this technical potential could be realised in practice.

We projected the mitigation potential of land sparing in the United Kingdom with reference to its binding commitment to reduce emissions by 80% by 2050 (relative to 1990 levels)[7]. We began by identifying a technically plausible range in the future yields of all major crop and livestock commodities produced in the UK, based on historic trends and future potential. We define yields as the annual tonnage of production per hectare for crops and the feed conversion ratio (feed consumed per kilogram of production) for livestock. Future yields could vary across a wide range, driven by a number of biophysical, technical and socioeconomic factors[8–11]. We assessed the likely bounds of this range based on an assessment of technical potential and reflect this in our projections, which span yield declines through to sustained long-term growth averaging 1.3% per annum across all commodities

(Table 1; Supplementary Fig. 1; Supplementary Discussion). For the avoidance of doubt, we do not equate our lower yielding scenarios with ‘land sharing’.

We next projected emissions attributable to UK agricultural production out to 2050, quantifying all sources of emissions that would be affected by a land-sparing strategy. We therefore quantified not only emissions reported under ‘Agriculture’ in the UK’s greenhouse gas inventory[12], but also emissions related to agriculture but reported in other sectors (e.g. farm energy use, agro-chemical production and land-use change), and emissions arising overseas due to imported feed for livestock (see Supplementary Table 2 for all emissions sources quantified). Our projections assumed that agricultural production increases from present levels in proportion to projected demand growth (Supplementary Table 1). In certain scenarios, projected UK farming capacity does not keep pace with demand growth. In such cases we assumed an increase in imports and accounted for the overseas emissions associated with those imports.

Next we formulated a land-sparing strategy. As yields increase, the area of farmland required for a given level of production declines, allowing land to be spared. Our definition of land sparing includes the active restoration of habitats on spared land and our main scenario assumed the restoration of wet peatland (on spared organic soils) and native broadleaved forest (on spared mineral soils) (Supplementary Table 3). We quantified the greenhouse gas fluxes from the soils and biomass of these habitats, drawing on the UK’s carbon accounting methodology[12] and IPCC guidelines[13].

The fourth step in our calculation was to combine emissions from farming with emissions from land-use change and compare projected net emissions in 2050 with the equivalent baseline emissions in 1990 (Supplementary Table 2). We find that there is significant scope to mitigate emissions through land sparing (Fig. 1a). At the lower-bound of our yield projections, emissions are projected to increase relative to current levels, reflecting increased agricultural production in 2050. In contrast, if yield growth towards the upper-bound of our projections could be realised, emissions from farming are lower (due primarily to more efficient livestock production; Fig. 1b) and the active restoration of habitats on spared land leads to significant carbon sequestration. The upper-bound of technical potential approaches a decline in net emissions of 80% relative to the 1990 baseline (the UK's greenhouse gas reduction target), though economic and implementation considerations are likely to limit the degree to which that technical potential could be realised in practice.

To explore the scope for combining emissions reduction strategies, we next assessed two promising demand-side measures[14] implemented alongside land sparing. We quantified the effect of replacing some animal products in the diet with vegetarian substitutes (Fig. 2a) and the effect of reducing food waste (Fig. 2b), in both cases maintaining the land-sparing strategy based on active restoration of natural habitats. Reducing meat consumption appears to offer greater mitigation potential than reducing food waste, but more importantly, our results highlight the benefits of combining measures. For example, coupling even moderate yield growth with land sparing and reductions in meat consumption has the technical potential to surpass an 80% reduction in net emissions (Fig. 2a).

Last, we quantified the technical mitigation potential of a number of possible alternative uses of spared land: allowing natural regeneration (a low-cost option); establishing faster growing coniferous rather than native broadleaved forest; and growing bioenergy crops (which can mitigate emissions by displacing fossil fuels) (Fig. 3). We find that actively restoring forest increases the rate of carbon sequestration compared with natural regeneration, and coniferous woodland sequesters more carbon than native broadleaved woodland. Our results suggest that the mitigation potential of oilseed rape for biodiesel is negligible, and the potential of

Miscanthus and short-rotation coppice depends strongly on the fossil fuel being displaced, only outperforming natural regeneration if displacing coal.

The scenarios we have assessed indicate that land sparing offers the technical potential for substantial mitigation. The degree to which that technical potential could be realised in practice depends on a number of factors. Our upper-bound scenario entails large, ongoing and environmentally sustainable increases in farm yields. A key issue, therefore, is identifying the mechanisms that could contribute to this outcome. Rates of yield growth in key crops have declined in recent years (Supplementary Fig. 1). Competing hypotheses explain the decline (see Supplementary Discussion). The first argues that insurmountable biophysical limits are constraining yield growth[9], a situation that might be compounded by climate change[15], and this outcome is reflected at the lower-bound of our yield projections. The second hypothesis argues that yields are well within biophysical limits, but that regulatory and market conditions and declines in research and development have reduced incentives to invest in yield growth[9–11]. These factors are controllable so under the second hypothesis there is significant scope for future yield growth. Our results highlight the technical potential for substantial mitigation if these barriers to yield growth can be overcome as part of a land-sparing strategy.

A large proportion of projected upper-bound mitigation arises due to assumed growth in livestock productivity (Fig. 1b). Our upper-bound livestock productivity gains (Table 1) assume that technological advancements lead to continued genetic gains through breeding, coupled with improved livestock health and nutrition. These gains contribute approximately half of the upper-bound mitigation in 2050 (Fig. 1b) but might be untenable in practice on economic, animal welfare or technical grounds and we note that other studies predict much lower future livestock productivity growth in Europe (see Supplementary Discussion). Encouragingly however, if even moderate productivity gains could be realised and coupled with policies that encourage reduced meat diets, technical mitigation potential is pronounced (Fig. 2a). Altering consumer dietary preferences is challenging, but aided by expected health benefits[16], a number of policy options are available. Taxes and subsidies in particular are demonstrably effective at driving diet change[17] (see Supplementary Discussion).

We have assessed the technical potential but not the economic feasibility of a land-sparing strategy. UK land use and production decisions are affected by global food prices[18], so realising land sparing in practice requires policies that couple yield increases with habitat restoration on spared land. In the UK, the obvious mechanism to effect this is via reform of the EU's Common Agricultural Policy[18]. Any mechanism would need to be carefully designed so as to function given the UK's role in the world food economy. Leakage and rebound effects might reduce the mitigation achieved, and increases in global food prices might compromise a land-sparing strategy by creating an incentive to farm, rather than spare, land[19,20]. Integrating our approach with models linking the global agricultural economy, land use and the changing climate[21] would enable a broader assessment of land sparing in the context of global markets, emissions and food security. Economic considerations will also inform the most appropriate use of spared land. Natural regeneration represents a low-cost option, so any incremental mitigation benefits from managed forestry or bioenergy should be balanced against the additional management costs under these options. Similarly, displacing fossil fuels using bioenergy might not be the best overall strategy: if the UK energy sector could reduce emissions by 80% using other clean energy sources (thereby limiting the mitigation achievable using bioenergy), using spared land to grow forests rather than bioenergy crops would result in greater overall mitigation.

Our results are robust to uncertainties in key parameters (Supplementary Table 4; Supplementary Fig. 2), but need to be interpreted cautiously. Firstly, restored habitats will – over a period of one hundred or more years – eventually reach a new equilibrium and net carbon sequestration will decline to zero[1,22]. Actively managing the carbon sink by growing bioenergy crops or by managing forests for fuel-wood or timber might in some circumstances extend the timeframe for mitigation[23], but might also compromise biodiversity objectives. Secondly, climate change feedbacks might affect our findings by altering soil carbon dynamics and the yields of food crops, livestock, bioenergy crops and trees. However, these effects are likely to be reduced by adaptation measures[15,24], and provided that non-farmed habitats continue to store much more carbon than farmland we think our conclusions will hold. Thirdly, it is essential to assess the sustainability of yield increases[25]. For example, due regard for animal welfare, local air and water quality and soil function is essential when increasing yields[8,25]. Encouragingly, the techniques we consider that increase yield also have the potential to reduce externalities per unit of production (Supplementary Table 5) and modern livestock breeding techniques allow multiple traits, including health, welfare and productivity, to be considered simultaneously[8] (see Supplementary Discussion). Last, managing water resources in higher-yielding landscapes will require a focus on improving water use efficiency in crops alongside careful spatial planning of spared land.

Land sparing would have far reaching implications for the UK countryside and would affect landowners, rural communities, ecosystem services and biodiversity. Our projections in Fig. 1 would result in UK forest cover increasing from 12% to reach 30% by 2050 – close to that of Germany and France but still less than the European average[26] – and the restoration of up to 0.7 Mha of wet peatland (Supplementary Table 3). Such large-scale restoration is likely to benefit ecosystem service provision, including water purification, recreation and flood mitigation[18,27]. Land sparing has the potential to be beneficial for biodiversity, including for many species of conservation concern[6,27,28], but benefits will depend strongly on the use of spared land. In addition, high yield farming involves trade-offs and is likely to be detrimental for wild species associated with farmland. Careful implementation – by retaining seminatural pastures of high conservation value, for example – will be important to minimise any detrimental impacts. Growing bioenergy crops on spared land (rather than land needed for food production) addresses concerns over indirect land-use change[1], but compared with natural habitats might compromise ecosystem services and biodiversity objectives[29].

Finally, how relevant are our results to other parts of the world? The UK presents a challenging test for the implementation of a land-sparing strategy. Relatively low yield gaps in the UK[30] mean that achieving yield increases into the long term will require continued genetic advances. This is compounded by relatively high projected demand growth in the UK driven by a projected population increase of 26% over the forecast period (Supplementary Table 1). In contrast, in many global regions, yield gaps are quite large[30] compared with projected growth in agricultural demand[5] (Supplementary Fig. 3). Clearly the technical and economic feasibility would need to be assessed in each location, but our findings suggest that land sparing may be a promising strategy for reducing greenhouse gas emissions from agriculture and land-use change in several parts of the world besides the UK.

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Author contributions A.B., A.L. and R.G. conceived the study. A.L. conducted the analysis and prepared the manuscript. A.H., D.K., E.W., K.G., P.C., P.S. and R.F supplied data. All authors contributed in the writing and editing of the manuscript.

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Table legends

Table 1: Scenarios of yield and feed conversion ratio

Commodity	Yield (t ha^{-1} yr^{-1}) or FCR (MJ kg^{-1}) 2010	2050 Lower-bound	2050 Upper-bound	Average rate of change 2010-2050 (% yr^{-1}) Lower-bound	Upper-bound†
Cereals	7.0	6.5	13.0	-0.2%	1.6%
Oilseeds	3.5	3.5	6.8	0.0%	1.7%
Potatoes	43.7	43.7	74.0	0.0%	1.3%
Sugar beet	68.0	68.0	113.0	0.0%	1.3%
Fruit and vegetables	20.0	20.0	30.0	0.0%	1.0%
Forage maize	8.1	7.1	10.7	-0.3%	0.7%
Forage legumes	3.7	3.7	6.0	0.0%	1.2%
Other forage crops	7.6	7.6	12.3	0.0%	1.2%
Temporary grass*	1.0	1.0	1.8	0.0%	1.5%
Permanent grass*	1.0	1.0	1.8	0.0%	1.5%
Rough grazing*	1.0	1.0	1.0	0.0%	0.0%
Beef meat	147	147	98	0.0%	-1.0%
Milk	11	11	7	0.0%	-1.0%
Pig meat	38	38	25	0.0%	-1.0%
Sheep meat	214	214	161	0.0%	-0.7%
Poultry meat	33	33	24	0.0%	-0.8%
Eggs	31	31	23	0.0%	-0.8%

Crop yields and livestock feed conversion ratios (FCRs) in 2010 and lower- and upper-bound assumptions in 2050. FCRs apply to animals producing meat, milk or eggs, not the entire herd; a negative change indicates improving feed conversion efficiency. *For modelling purposes, grassland yields are expressed relative to the 2010 yield which was set to a value of 1. †Mean upper-bound yield growth of 1.3% yr^{-1} reported in the text is the average of the figures shown (with FCR growth expressed as a positive quantity), weighted by the energy content of production of each commodity in 2010.

Figure legends

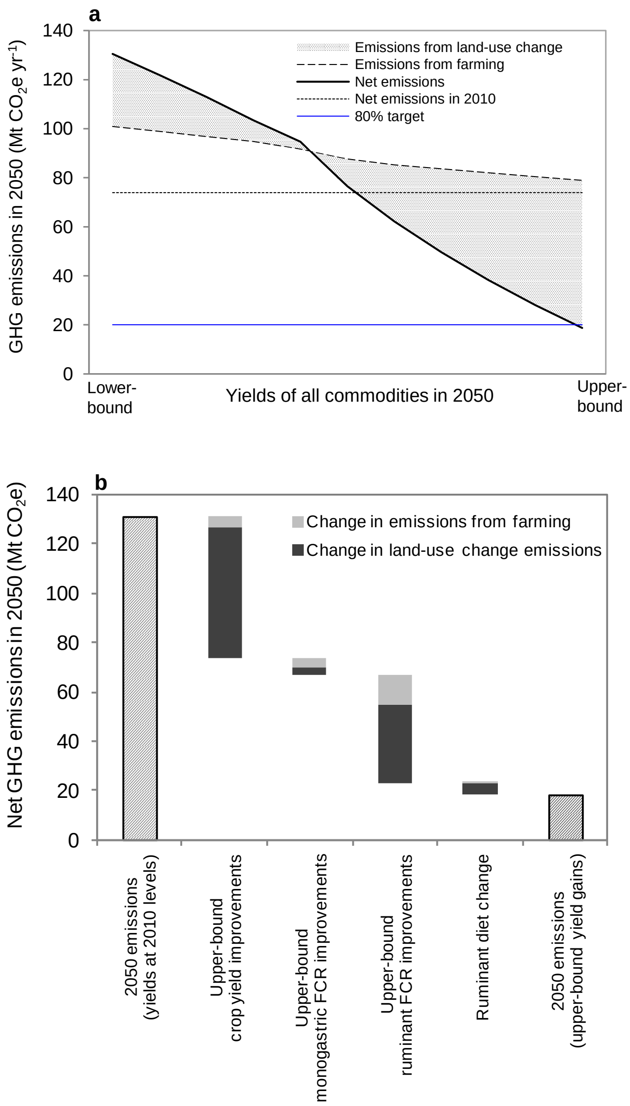

Figure 1. Mitigation of greenhouse gas emissions from agriculture by land sparing. a. Net greenhouse gas (GHG) emissions in 2050 are shown as the sum of emissions from farming and emissions from land-use change (which may be positive or negative). Yields of all commodities in 2050 are scaled linearly between the lower- and upper-bounds shown in Table 1. Emissions representing an 80% reduction relative to baseline net emissions in 1990, and equivalent net emissions in 2010, are shown for reference (20.1 Mt CO_2e yr^{-1} and 73.9 Mt CO_2e yr^{-1} respectively, see Supplementary Table 2). **b**. Contribution of crop yield and

livestock feeding efficiency gains to projected upper-bound mitigation in 2050. Projected net emissions in 2050 with yields, FCRs and ruminant diets at 2010 levels (left-hand bar; see Table 1); the effect of upper-bound assumptions (Table 1) on emissions from farming and land-use change emissions (intermediate bars); and the cumulative effect of all changes, projected net emissions in 2050 under upper-bound yield assumptions (right-hand bar).

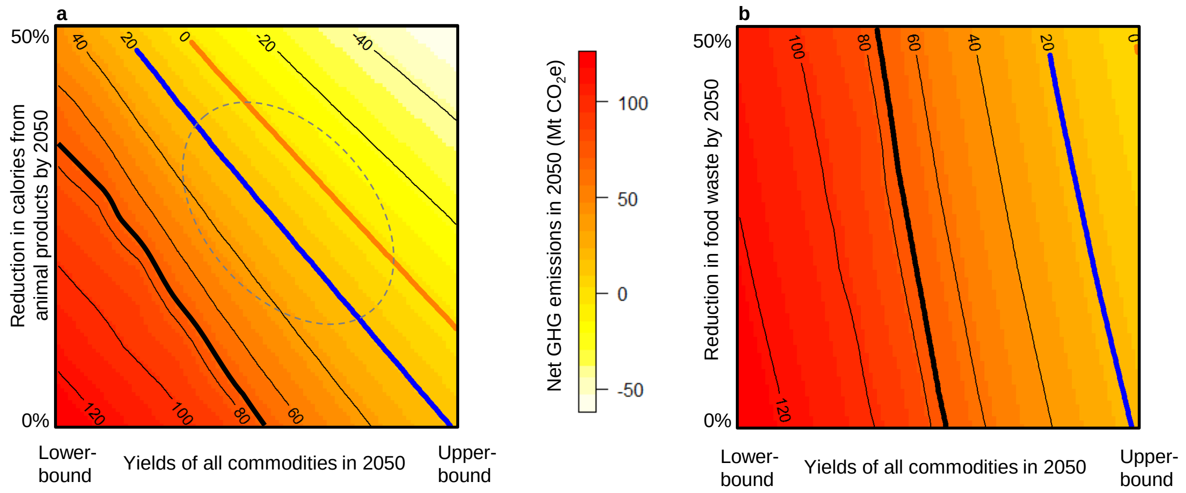

Figure 2: **Greenhouse gas mitigation by coupling land sparing with demand management. a.** Reduction in the consumption of animal products. Shading and contours indicate net greenhouse gas (GHG) emissions in 2050 as a function of the reduction in calories from animal products by 2050 (vertical axis; see Supplementary Methods) and yields in 2050 (horizontal axis; scaled linearly between the lower- and upper-bounds shown in Table 1). Emissions representing an 80% reduction relative to baseline net emissions in 1990 (thick blue contour; 20.1 Mt CO_2e yr^{-1}), equivalent net emissions in 2010 (thick black contour; 73.9 Mt CO_2e yr^{-1}) and zero net emissions (thick orange contour) are also shown for reference. The enclosed dashed region indicates the mitigation potential of coupling moderate reductions in meat consumption with moderate yield increases under land sparing. **b.** Reduction in food waste. As for (a) but the vertical axis represents the reduction in post-harvest food waste by 2050 (see Supplementary Methods).

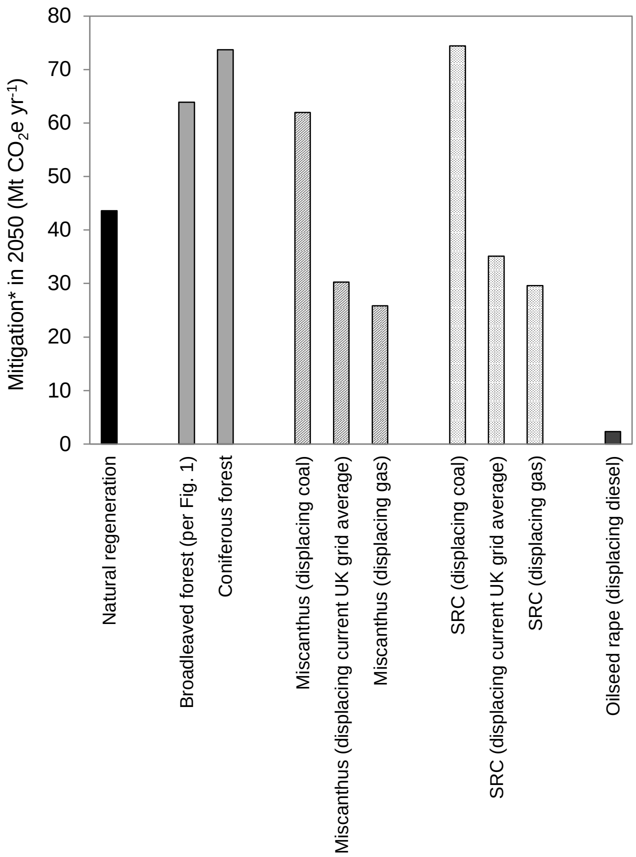

Figure 3: **Upper-bound mitigation potential in 2050 under different uses of spared land.** Results assume upper-bound yield increases and different uses of spared land: natural regeneration; broadleaved woodland (the main scenario presented in Fig. 1); coniferous woodland; and bioenergy crops. *Miscanthus* and short-rotation coppice (SRC) are shown assuming three different fossil fuel displacement pathways: coal, the current UK electricity grid average, and natural gas. *The nature of mitigation is different depending on the use of spared land. Mitigation under natural regeneration and forestry is primarily due to carbon sequestered in the soils and biomass of restored habitats and would normally be reported in the 'Land use, land-use change and forestry' sector. For bioenergy crops, the mitigation arises primarily due to avoided emissions from displaced fossil fuels, and would normally be reported in the energy sector.